APPENDIX Q

FINITE ELEMENT PROGRAM TO CALCULATE STRESS INTENSITY FACTOR

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INTRODUCTION

It is well known that pavement crack propagation is influenced by traffic load, climate, material properties, pavement structure, and many other interacting variables. Many studies have been conducted to address this problem, and different models such as the fracture mechanics model (48) have been proposed to analyze and/or predict the crack propagation. After reviewing these models, it was concluded that the finite element (FE) plus fracture mechanics-based crack propagation model is conceptually sound and can be easily implemented within current mechanistic-empirical (ME) pavement design framework (49, 50). The fundamental principle of this model is to calculate the stress intensity factor (SIF) induced by traffic loading (bending SIF and shearing SIF) and daily temperature variation (thermal SIF). Therefore, a fast and accurate SIF computational tool, capable of considering a three-dimensional (3D) pavement structure, becomes an indispensable analytical tool.

First of all, this appendix discusses the background of the fracture mechanics approach and the available FE analysis tools for pavement crack propagation analysis. The new developed FE analysis tool "SA-CrackPro" and its features are then introduced. The key implementation method of the SA-CrackPro is discussed in detail, and its accuracy is also verified by comparing the results with a commercial 3D FE package ANSYS. Finally, the tool's potential applications are discussed and demonstrated.

BACKGROUND OF THE FRACTURE MECHANICS APPROACH AND ASSOCIATED SIF COMPUTATION TOOLS

Among the various laws that have been conceptualized, Paris' law (11) is still the governing concept for modeling crack propagation, particularly for fracture-micromechanics applications. Expressed in Equation Q-1, Paris' law has been successfully applied to HMA mix by many researchers, for the analysis of experimental test data and prediction of reflective- and low temperature-cracking (1, 51).

$$\frac{dc}{dN} = A * (\Delta K)^n \qquad \text{(Q-1)}$$

Note: this appendix was written by Sheng Hu, Xiaodi Hu, Fujie Zhou, and Lubinda Walubita, all of the Texas Transportation Institute, Texas A&M University

where, c is crack length; N is number of loading cycles; A and n are fracture properties of HMA mixture determined by lab testing; and ΔK is the SIF amplitude, depending on the geometry of pavement structure, fracture mode, and crack length.

The number of loading cycles N_f needed to propagate a crack (C_o) through the pavement thickness, h, can be estimated by numerical integration in the form of Equation Q-2.

$$N_f = \int_{C_0}^{h} \frac{dc}{A(\Delta K)^n} \tag{Q-2}$$

Apparently, SIF is one of the key parameters in Paris' law. Consequently, the rapidness and accuracy of computing SIF values becomes a very critical aspect of crack propagation analysis. Currently, two categories of SIF computation tools are available.

The first category includes commercial FE packages (such as ABAQUS, ANSYS, etc) which are general- or rather multi-purpose. It is no doubt about the capability and accuracy of these FE packages, but their complex nature and user-unfriendliness comes at a price. Due to their complexity, intensive training is often required. This is very time consuming and often not very ideal for most practicing pavement engineers and researchers. Furthermore, these commercial FE packages are relatively costly and require licenses. As a result, only very engineering firms and institutions own these commercial FE packages. Thus, in practicality these commercial FE package cannot be readily utilized for routine crack propagation analysis and pavement design.

The second category is those FE tools specifically developed for pavement SIF computation. Currently, two SIF computation programs have already been developed for pavement analysis. The first one named CRACKTIP was developed for thermal cracking by Lytton and his associates (52) at the Texas Transportation Institute in 1976. The CRACKTIP was a 2D FE program, and it modeled a single vertical crack in the HMA layer via a crack tip element. This program has been successfully used to develop the thermal SIF model for low-temperature cracking prediction in the SHRP A-005 research project (4). However, it is well known that the difference between 2D plane strain conditions and the 3D nature of a cracked pavement and traffic loading often leads to a significant overestimation of the displacements and consequently the computed SIF values under the same load. The other pavement SIF program named "CAPA" (Computer Aided Pavement Analysis) was developed at the Delft University of Technology in the 1990s (53, 54). The CAPA-3D program has some special functions to address the reflection cracking issue; such as special elements for simulating interface and interlayer, automatic remeshing techniques to simulate crack propagation, etc. All of these functions make the CAPA-3D a good option for crack propagation analysis. Unfortunately, due to its 3D characteristics, the high hardware and execution time demands render it suitable primarily for research purposes.

It thus appears that there are at present few 3D FE tools that are relatively inexpensive and would allow the practitioners to routinely interpret this complex but frequently encountered pavement crack analysis situations. Thus there is great need to find a means to both improve the calculation speed and reduce the resource requirement without the loss of accuracy. This was the primary objective of the work presented in this appendix.

SA-CRACKPRO: A NEW CRACK PROPAGATION ANALYSIS TOOL AND ITS GENERAL FEATURES

One of the methods that seem most promising for achieving the aforementioned objective is the method known as Semi-Analytical (SA) FE method. This method can effectively transform a 3D pavement analysis problem to an equivalent 2D model pavement, at a significant saving in terms of the computational effort (55). Built on this method, a new specific pavement crack propagation analysis tool, *SA-CrackPro*, was developed. The main features of this *SA-CrackPro* are presented as follows.

Computational Efficiency

Due to the reduction in dimensional analysis, *SA-CrackPro* has much smaller number of equations and a matrix with a narrower bandwidth than the 3D FE programs. Also, it has a much smaller amount of input and output data because of the smaller number of nodes. Consequently, it needs much shorter computing time, input data preparation time, and resulting cleaning up time. This computational efficiency makes it possible to extensively analyze crack propagation in fatigue and reflection cracking prediction analysis.

Isoparametric Quadratic "Quarter-Point" Element

To determine SIF values, a fundamental difficulty is the fact that the polynomial basis functions used for most conventional elements cannot be utilized to represent the singular crack tip stress and strain fields predicted by the fracture mechanics theory. So a number of researchers have investigated special FE formulations that incorporate singular basis functions as nodal variables. While successful, these special purpose elements are not available in most general purpose FE programs and thus are used very infrequently.

A significant milestone in this area was the "quarter-point" elements discovered by Henshell and Shaw (56) in 1975 and Barsoum (57) in 1976. These researchers showed that the proper crack-tip displacement, stress, and strain fields can be modeled using isoparametric finite elements with standard quadratic order, if one simply moves the element's mid-side node to the position one quarter of the way from the crack tip to the far end of the element. Since these elements are standard and widely available, FE programs can easily be used to model the crack tip fields accurately with only minimal preprocessing required. The “quarter-point” element is extremely important to any FE program for crack propagation including *SA-CrackPro*, because it is not only easily implemented, but the SIF value computed from *SA-CrackPro* also seems pretty stable when adopting different meshing sizes in a reasonable range.

Thin-Layer Elements for Simulating Pavement Layer Contact Condition and Load Transfer Efficiency at Joints/Cracks

It is a well known fact that contact conditions between the pavement layers have significant influence on pavement response and accordingly on crack propagation. Thus, it is ideal for a crack propagation analysis tool (such as *SA-CrackPro*) to have the capability to simulate various pavement layer contact conditions from fully continuous to fully slipping. This is also true for the load transfer conditions at joints and/or cracks due to the aggregate interlock or the joint load transfer in PCC pavements. To simulate these conditions, the concept of thin-layer interface elements was used in *SA-CrackPro*. The advantages of using the thin-layer interface elements are listed below:

- The thin-layer element method can provide satisfactory solutions;
- It can be computationally more reliable than the zero thickness elements; and
- It is possible to handle various deformation modes such as fully continuous, fully slipping, or in between.

Automatic Meshing and Re-meshing Technique for Crack Propagation

Finite element meshing is always an uneasy work, especially for a cracked pavement structure, such as an HMA overlay over PCC pavements. For a specific crack, both quarter elements surrounding the crack tip and standard elements are required. Furthermore, these elements have to be re-meshed along each crack increment, which often makes crack propagation and the associated SIF computation tedious. To overcome these difficulties, a series of element meshing and re-meshing algorithms were developed and implemented in *SA-CrackPro*. With known pavement structure thickness, material properties (modulus and Poisson ratio), and crack length, *SA-CrackPro* can automatically simulate the crack propagation in the vertical direction towards the pavement surface and calculate the corresponding SIF values.

To further describe the *SA-CrackPro* program, this appendix discusses how to achieve these features and provides some details of the methods implemented in the *SA-CrackPro* program in the following section.

DESCRIPTION OF THE KEY METHODS IMPLEMENTED IN *SA-CRACKPRO* PROGRAM

SA FE Method

The basic procedure in the FE formulation is to express the element coordinates and element displacements in the form of interpolations using the natural coordinate system of the element.

In the *SA-CrackPro* program, the 8 node isoparametric elements (in the *X*-*Y* plane, see Figure Q-1) are used, and the displacement functions are given by Equation Q-3:

$$
\begin{aligned}
u(x,y,z) &= \sum_{l=1}^{L}\sum_{k=1}^{8} N_k u_{kl} Z_{1l}(z) \\
v(x,y,z) &= \sum_{l=1}^{L}\sum_{k=1}^{8} N_k v_{kl} Z_{2l}(z) \qquad \text{(Q-3)} \\
w(x,y,z) &= \sum_{l=1}^{L}\sum_{k=1}^{8} N_k w_{kl} Z_{3l}(z)
\end{aligned}
$$

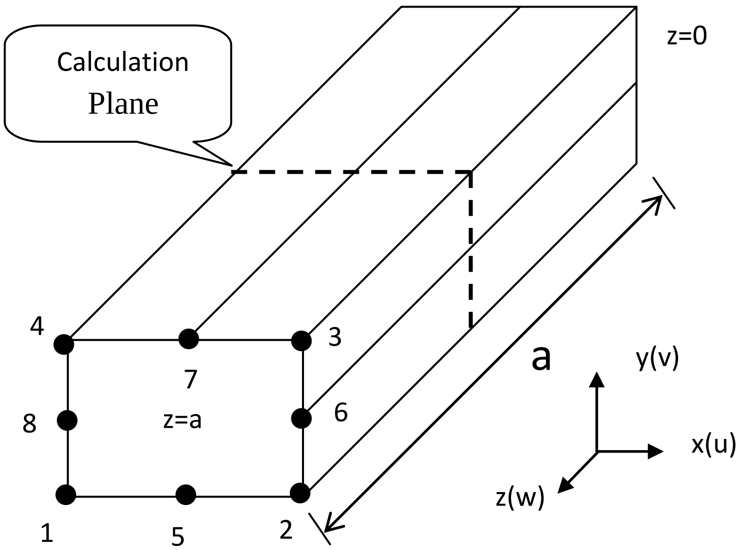


Figure Q-1. 8-nodes isoparametric element in X-Y plane.

where, l identifies the l^{th} term of the Fourier series and L is the total number of terms considered, Z_{1l}(z), Z_{2l}(z), Z_{3l}(z) (Equation Q-4) are 3 analytical functions along the z direction in the *SA-CrackPro* program.

$$Z_{1l}(z) = Z_{2l}(z) = Sin\frac{l\pi z}{a},\ Z_{3l}(z) = Cos\frac{l\pi z}{a} \quad 0 \leq z \leq a \qquad \text{(Q-4)}$$

N_k is the same interpolation function used to express displacement for the 2D problem in an *X-Y* plane; u_{kl}, v_{kl}, and w_{kl} are the k^{th} node displacements in the l^{th} term along the x, y, z directions, respectively.

A typical sub-matrix of the element stiffness matrix $[k]^e$ is:

$$\left[k^{lm}\right]^e = \iiint_{Vol}\left[B^l\right]^T[D]\left[B^m\right]dxdydz \qquad \text{(Q-5)}$$

Also, a typical term for the force vector F is:

$$\left[F^{l}\right]^{e} = \iiint_{Vol} \left[N^{l}\right]^{T} \{p\}^{l}\, dxdydz \tag{Q-6}$$

Where, l and m identify the l^{th} and m^{th} terms of the Fourier series, respectively, and [B] is the strain-displacement matrix.

As pointed out by Zienkiewicz (55), the matrix given in Equation Q-5 contains the following integrals:

$$\begin{aligned} I_1 &= \int_0^a \sin\frac{l\pi z}{a}\cos\frac{m\pi z}{a}\,dz \\ I_2 &= \int_0^a \sin\frac{l\pi z}{a}\sin\frac{m\pi z}{a}\,dz \\ I_3 &= \int_0^a \cos\frac{l\pi z}{a}\cos\frac{m\pi z}{a}\,dz \end{aligned} \tag{Q-7}$$

The integrals exhibit the orthogonal property which ensures that:

$$I_2 = I_3 = 0 \quad \text{for } l \neq m \tag{Q-8}$$

Also, this orthogonal property causes the matrix $[k]^e$ to become diagonal. The final assembled equations for the problem have the following form:

$$\begin{bmatrix} \left[K^{11}\right] & & & \\ & \left[K^{22}\right] & & \\ & & \cdots & \\ & & & \left[K^{LL}\right] \end{bmatrix} \begin{Bmatrix} \delta^1 \\ \delta^2 \\ \cdots \\ \delta^L \end{Bmatrix} + \begin{Bmatrix} F^1 \\ F^2 \\ \cdots \\ F^L \end{Bmatrix} = 0 \tag{Q-9}$$

Equation Q-9 shows that the large system of equations splits into L separate problems. As noted by Zienkiewicz (54), this orthogonal property is of extreme importance for the SA FE method, because, if the expansion of the loading factors involves only one term for a particular harmonic, then only one set of simultaneous equations needs to be solved. Thus, what was originally a 3D problem now has been reduced to a 2D model problem. More theoretical justification can be found in the literature (56). Here it should be noted that, for each problem calculation, the SA FE method provides the output only along a single *X-Y* plane at a user specified *z*-coordinate. An example of such a plane is shown by broken lines in Figure Q-1.

"Quarter-Point" Element and SIF Calculation Method

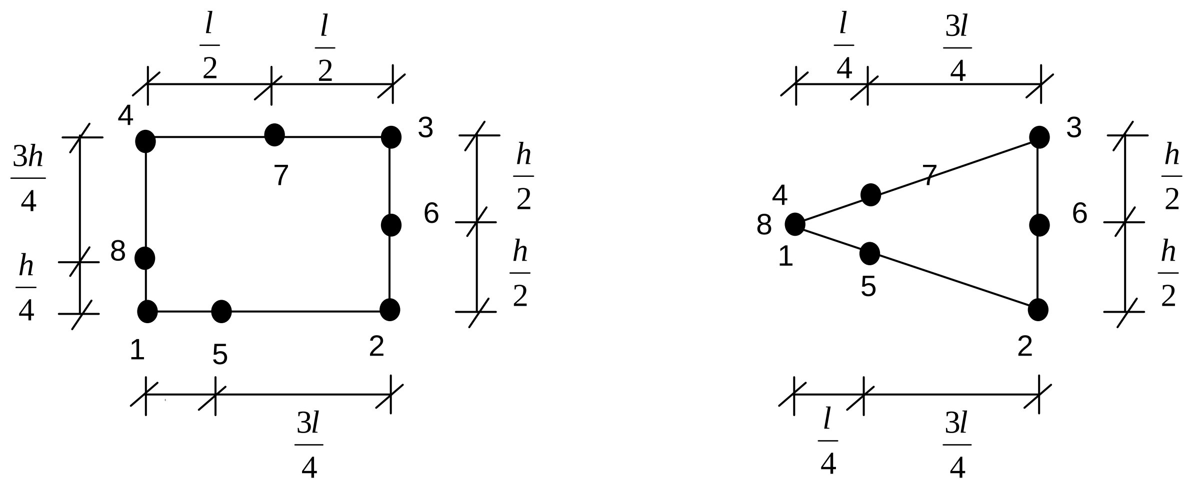
As mentioned previously, Henshell and Shaw (56) described a quadrilateral quarter-point element illustrated in Figure Q-2a. Barsoum (57) proposed collapsing one edge of the element at the crack tip, where the crack-tip nodes (1, 4, 10) are constrained to move together, as shown in Figure Q-2b.

The expressions for extracting the SIF values using plane strain assumptions (58) are given in Equations Q-10 and Q-11, and the corresponding FE meshing around the crack tip is shown in Figure Q-3.

$$K_I = \frac{G\sqrt{2\pi}}{\sqrt{r_{a-b-c}}(4-4\mu)}[4(u_d - u_b) + (u_c - u_e)] \qquad \text{(Q-10)}$$

$$K_{II} = \frac{G\sqrt{2\pi}}{\sqrt{r_{a-b-c}}(4-4\mu)}[4(v_d - v_b) + (v_c - v_e)] \qquad \text{(Q-11)}$$

where, r_{a-b-c} is the distance from a crack tip point '*a*' to point '*c*'; K_I and K_{II} are SIF values for Mode I (opening crack mode) and Mode II (shearing crack mode), respectively; G is the shearing elastic modulus (= $\frac{E}{2(1+\mu)}$ for isotropic elements); μ is Poisson's ratio; and u_i, v_i are the *x, y* displacements at point *i*.



(a) Quadrilateral quarter-point element *(b) Collapsed quadrilateral*

Figure Q-2. Quadrilateral (a) and collapsed quadrilateral quarter-point element (b).

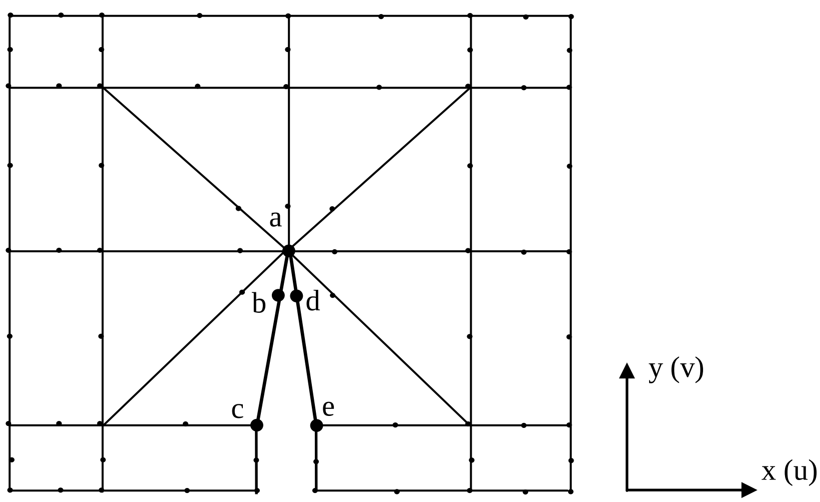


Figure Q-3. Finite elements meshing around crack tip.

Thin-Layer Element Method of Simulating Interfaces and Joints/Cracks

One of the commonly used interface elements is based on the joint element proposed by Goodman et al. (59). The element formulation is derived on the basis of relative nodal displacements of the solid elements surrounding the interface element. For a 2D analysis, the thickness of the element is often assumed to be zero, and the constitutive relation is expressed as:

$$\begin{Bmatrix} \sigma_n \\ \tau \end{Bmatrix} = \begin{bmatrix} k_n & 0 \\ 0 & k_s \end{bmatrix} \begin{Bmatrix} v_r \\ u_r \end{Bmatrix} = [C]_i \begin{Bmatrix} v_r \\ u_r \end{Bmatrix} \qquad \text{(Q-12)}$$

where, σ_n is the normal stress; τ is the shear stress; k_n is the normal stiffness; k_s is the shear stiffness; v_r and u_r are the relative normal and shear displacements, respectively; and $[C]_i$ is the constitutive matrix for the interface or joint element.

Based on the assumption that the structural and geological media do not overlap at interfaces, a high value, on the order of 10^8-10^{12} units, is assigned for the normal stiffness, k_n. However, it is arbitrary for adopting such high values. Furthermore, for modes such as debonding, the solutions are often unreliable (60).

As an improvement, Desai (60) proposed a method that uses a thin solid element to simulate interface behavior. Since the proposed element essentially represents a solid element of small finite thickness and a thin layer of material between two bodies, it is often referred to as a "thin-layer" element. The distinguishing features of Desai's work lie in the special treatment of the constitutive laws for the thin-layer element which considers the coupling effects of normal stiffness and shearing stiffness. Often, it was found that satisfactory results can be obtained by assigning the interface normal component the same properties as the adjacent geological material.

In the *SA-CrackPro* program, the interface and/or joint elements are defined as the orthotropic elements which have the same elastic modulus as that of the adjacent layers, but vary the shearing modulus to consider the shearing loading transfer between layers. This is one of the simplified applications of Desai's thin-layer method.

Regarding the thickness of the "thin-layer", Desai concluded that satisfactory simulation of the interface behavior can be obtained for *t/B* ratios (see Figure Q-4) in the range from 0.01 to 0.1(54). Pande and Sharma (61) reported that thin elements also provided satisfactory results for much lower *t/B* ratios. In the *SA-CrackPro* program, the *t/B* ratios were in the range from 0.0002 to 0.1. After massive SIF calculations, these ratios were found to be able to provide stable and reasonable SIF results.

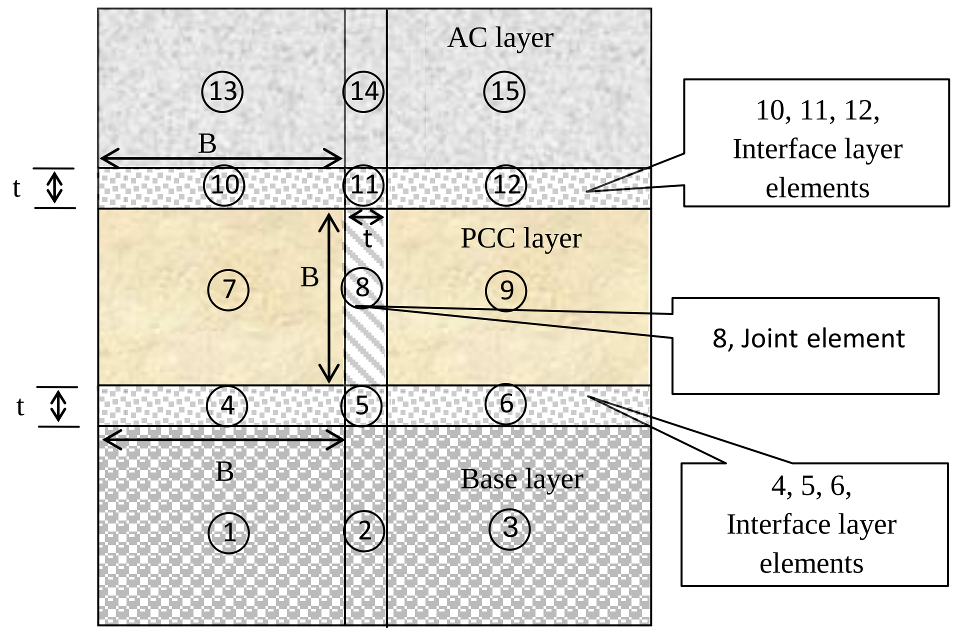


Figure Q-4. Thin-layer orthotropic elements in interface layer and joint.

Automatically Meshing and Re-meshing Method

For the *SA-CrackPro* program, the general inputs required are the number of total structure layers including the subgrade, layer moduli, layer Poisson ratios, layer thicknesses, contact condition between succeeding layers, load transfer conditions if joints/cracks exist, crack length, and initial crack location. As described previously, to form a singularity around the crack tip, the collapsed quadrilateral quarter-point elements must be used. Therefore, the basic idea of meshing is to distinguish the layer with the quarter point elements, then specially treat this layer when numbering the nodes and elements, and associated coordinates. Detailed steps are summarized below:

- Step 1: Determine the layer location of the crack tip based on the structural thicknesses and crack length *C*, see Figure Q-5.
- Step 2: Based on the layer location of the crack tip identified in Step 1, divide that layer into 2 or 3 sub-layers. If the crack tip is near the bottom of the pavement layer or near the top of this layer (Figure Q-5a and Q-5c), divide it into 2 layers; otherwise, divide it into 3 sub-layers (see Figure Q-5b).

- Step 3: Based on the results from Step 2, renumber the layers and recalculate the thickness of each sub-layer. Note that all the elements in these sub-layers have the same material property such as elastic modulus and Poisson ratio. Record the layer number in which the collapsed quadrilateral quarter-point elements are located.
- Step 4: Based on the results from Step 3, number each node and element and determine the corresponding coordinate of each node, and finally generate the meshing data file.
- Step 5: Load the meshing data file, and calculate the related node displacements and then compute the SIF value based on Equation Q-10 or Q-11.
- Step 6: Calculate the crack increment based on Equation Q-1, and re-calculate the total crack length. If the total crack length is longer than the specified layer thickness, then stop. Otherwise, go back to Step 1.

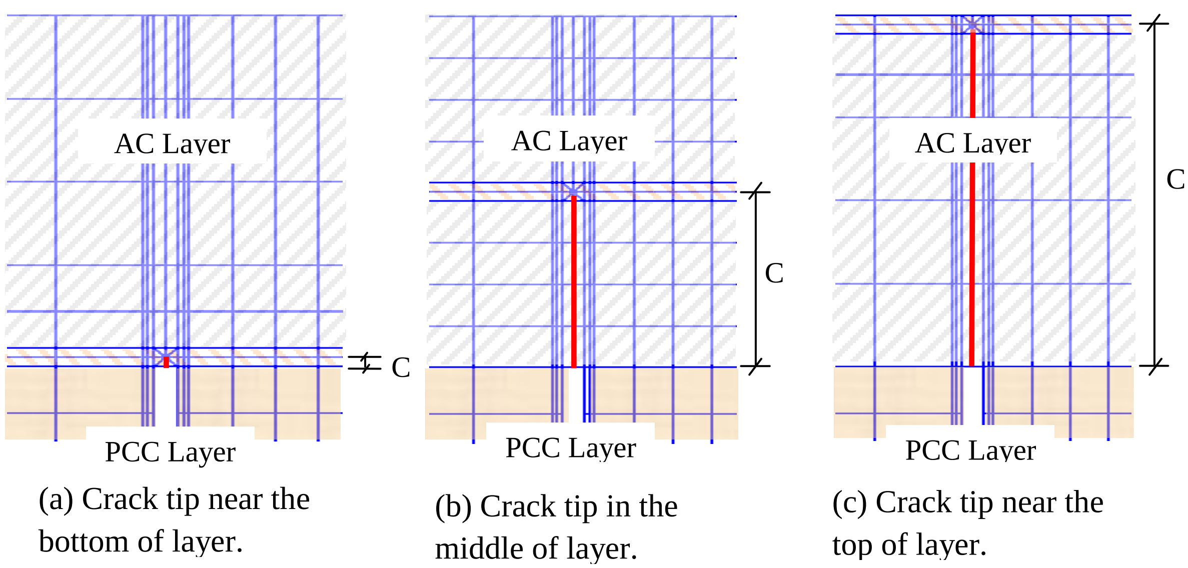


Figure Q-5. Finite element meshing and re-meshing based on crack tip location.

SA-CRACKPRO PROGRAM VERIFICATION

The efficiency of the SA method has been confirmed both theoretically and practically by many researchers (55, 62, 63). As Cheung et al. (63) pointed out that in some cases computational savings of a factor of 10 or more are possible due to the reduction in dimensional analysis. So in this paper, the major concern is the accuracy of the results of the *SA-CrackPro* program.

To verify the accuracy of *SA-CrackPro,* the side by side comparisons were conducted between ANSYS-3D (64) and *SA-CrackPro* under the same loading conditions for a same hypothetical pavement structure. Two cases were studied: one was a bending load mode for K_I verification and the other was a shearing load mode for K_{II} verification. The detailed information is presented below.

Typical Pavement Structure

Figure Q-6 shows the hypothetical pavement structure used for the verification. It is a two-laned pavement with shoulders; consisting of 4 layers: Asphalt Concrete Overlay (AC layer), Cracked Existing layer with a 4 mm wide crack, Base layer, and Subgrade.

The material properties and structural thicknesses are presented in Figure Q-6 as well. Five different crack lengths were considered in the comparison: C = 7.5, 22.5, 37.5, 52.5, and 67.5 mm, respectively. All pavement layers are assumed to be fully bonded and the zero load transfer assumption was used. The assumed traffic load is a standard single axle load of 80 kN with a tire pressure of 0.689 MPa. The detailed traffic loading position and tire contact area are shown in Figure Q-7.

Two fracture modes were analyzed in this appendix: bending mode and shearing mode. For the bending mode shown in Figure Q-8a, the axle load is immediately above the crack, and only K_I exists. For the shearing mode shown in Figure Q-8b, the axle load is on one side of the crack, and both bending and shearing SIFs exist. However, the shearing mode is dominant. Therefore, only the shearing mode K_{II} were calculated and compared in this case. Here it should be noted that in all these cases, the calculation plane is the *X-Y* plane which cuts through the center of the fourth tire (the outer tire), see Figure Q-8, the z coordinate of this plane is 7486.7mm, see Figure Q-7.

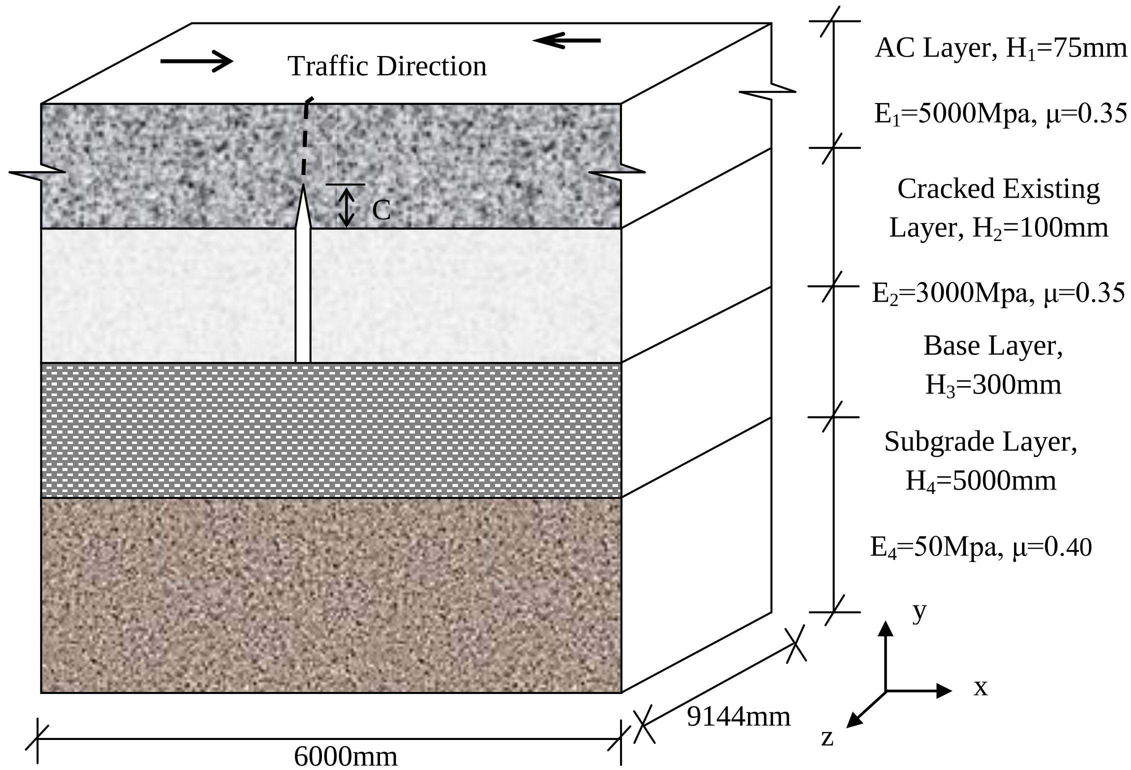
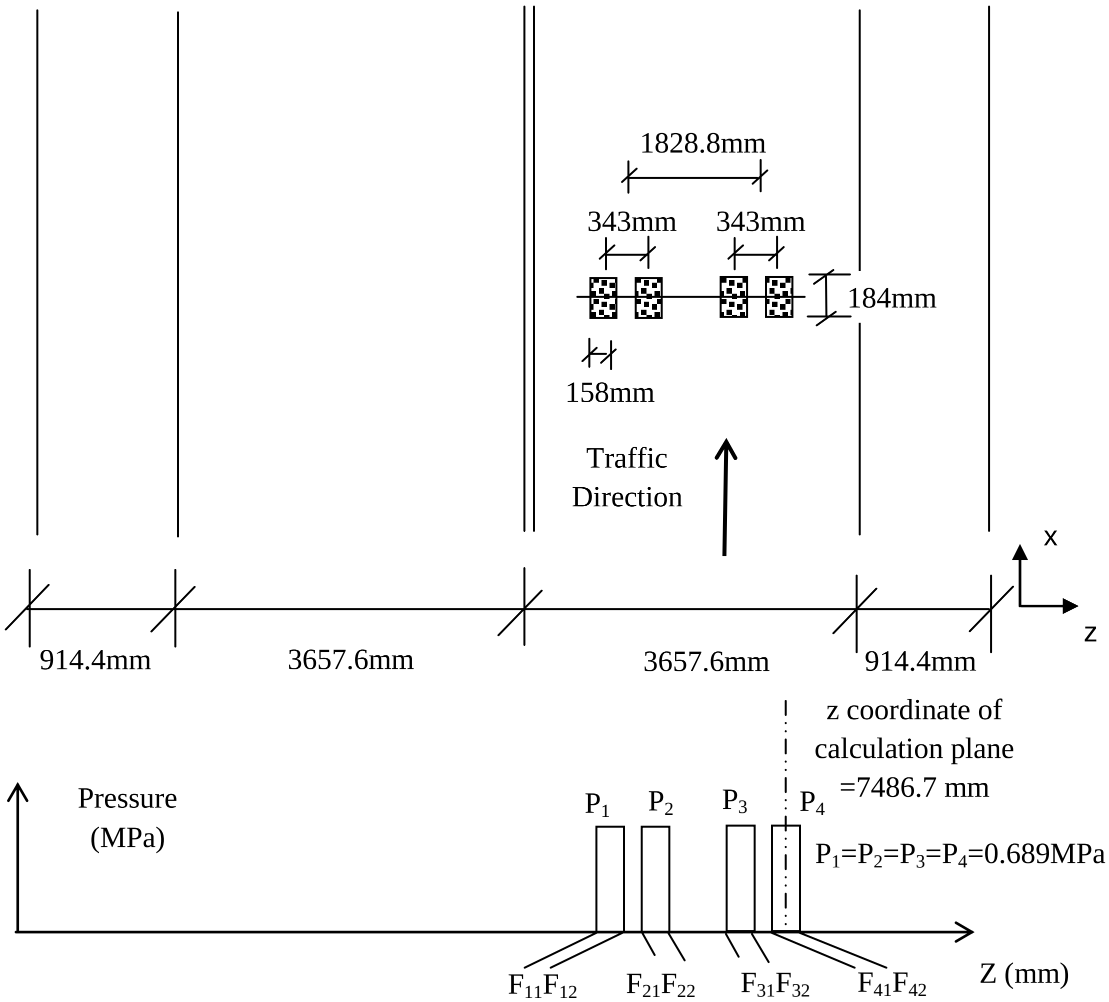


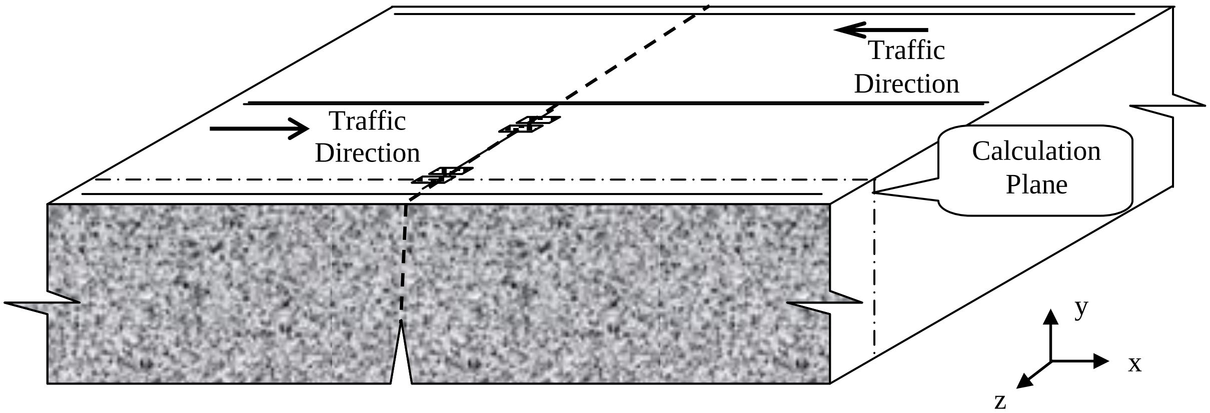
Figure Q-6. Pavement structure and parameters used for the verification study.



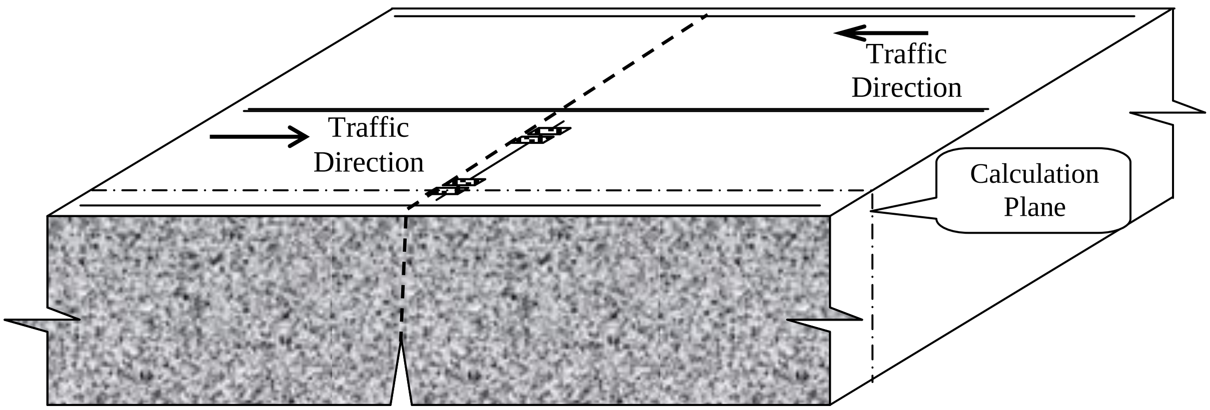
F_{11}=5235.9 mm F_{12}=5393.9 mm F_{21}=5578.9 mm F_{22}=5736.9 mm

F_{31}=7064.7 mm F_{32}=7222.7 mm F_{41}=7407.7 mm F_{42}=7565.7 mm

Figure Q-7. Detailed load information in X-Z plane.



(a) Bending mode: crack front is in the middle of the axle load area.



(b) Shearing load: crack front is at the edge of the axle load area.

Figure Q-8. Typical load form of bending (a) and shearing (b).

Table Q-1 presents the results from both ANSYS-3D and *SA-CrackPro* programs. Using the ANSYS-3D as the reference benchmark, the maximum error is 8.8%. Most errors are around ±5%. It is apparent that *SA-CrackPro* has an accuracy that is comparable with ANSYS-3D.

***SA-CRACKPRO* APPLICATIONS**

Since the SA method has a much shorter computing time than the 3D FE method, it becomes possible to directly integrate *SA-CrackPro* into the pavement design software to predict the crack propagation. Using *SA-CrackPro* this way has the benefit that the choice of structure can be very flexible during design and analysis. However, it is worth noting that, due to the FE nature, the computation speed of *SA-CrackPro* is between 2D FE and 3D FE program, if the *SA-CrackPro* program needs to be run many times during crack propagation analysis, the total analysis time will often take hours, which is still undesirable.

Table Q-1. SIF Comparison between SA-CrackPro and ANSYS-3D.

Crack Length (mm)	K_I (MPa* mm$^{0.5}$)			K_{II} (MPa* mm$^{0.5}$)		
	SA-CrackPro	ANSYS-3D	Error (%)	SA-CrackPro	ANSYS-3D	Error (%)
7.5	1.724	1.641	4.8	2.560	2.694	5.3
22.5	0.280	0.278	0.7	3.482	3.658	5.1
37.5	-2.115	-1.959	7.4	4.512	4.569	1.3
52.5	-5.786	-5.401	6.7	5.736	5.796	1.0
67.5	-13.652	-12.446	8.8	8.485	8.191	-3.5

To be more practical, another way of using *SA-CrackPro* is highly recommended. First, use *SA-CrackPro* to perform large scale SIF calculations. Second, develop SIF regression equations or Artificial Neural Network algorithms based on these calculations. Finally, integrate these SIF equations directly into pavement design and analysis software. In this way, crack propagation analysis time can often be reduced to a few seconds.

For the a purpose of demonstration, different four-layer pavement structures similar to Figure Q-6 are considered. The cracked existing layer is a Portland Cement Concrete (PCC) layer. The layer contact conditions are assumed to be fully bonded, except that between the PCC layer and the base layer, which is assumed to be half bonded. The detailed variations of the pavement structure configurations and layer properties are presented in Table Q-2. Note that only the shearing mode was analyzed and discussed as follows.

From Table Q-2, it can be determined that a total of 10935 (=3×5×3×3×3×3×9) runs were performed to complete a full factorial SIF calculation. It is nearly impossible to complete such large scale computations for other 3D FE programs, because such large quantities of input data preparation and output data cleaning up work often makes it very easy to make mistakes. However, for *SA-CrackPro*, the main inputs are just the information in Table Q-2, with which the tool automatically generates 10935 meshing data files and runs each file. Finally the well organized result summary file is generated automatically, which is ready to perform regression analysis. Note that in this case, the total input work only requires several minutes, and as long as these inputs are right, the 10935 definitely correct results will be obtained. A comparison between the calculated SIF-values and those predicted by a regression model is shown in Figure Q-9.

Table Q-2. Structure and material properties used for SIF analysis.

Main Parameter	**Range**	**Selected Values**	**Count Number**
H_1 (AC Layer Thickness, mm)	38-75	38, 75, 150	3
E_1 (AC Layer Modulus, MPa)	1000-20000	1000, 3000, 6000, 10000, 20000	5
H_2 (Existing Layer Thickness, mm)	200-400	200, 300, 400	3
E_2 (Existing Layer Moudlus, MPa)	20000-40000	20000, 30000, 40000	3
H_3 (Base Layer Thickness, mm)	100-400	100, 200, 400	3
E_3 (Base Layer Modulus, MPa)	100-10000	100, 1000, 10000	3
H_4 (Subgrade Thickness, mm)	5000	5000	1
E_4 (Subgrade Modulus, MPa)	30-150	50*	1
c/H_1 (ratio of crack length over H_1)	0.1-0.9	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9	9

** Since subgrade modulus did not have much influence on K_{II} value, only one typical value was used.*

SUMMARY AND CONCLUSIONS

A new pavement crack propagation analysis tool named *SA-CrackPro* was developed in this appendix. The main features of *SA-CrackPro* are 1) computational efficiency, 2) isoparametric quadratic "quarter-point" elements for SIF calculation, 3) thin-layer elements to simulate pavement layer contact condition and/or load transfer efficiency at joints/cracks, and 4) automatically meshing and re-meshing technique for crack propagation analysis. Additionally, a detailed discussion of these technical key components of *SA-CrackPro* was provided. Specifically, *SA-CrackPro* provides comparably accurate SIF computations which were verified by ANSYS-3D. Since *SA-CrackPro* has much shorter computing time than the 3D FE method, it becomes possible to be directly integrated into pavement design and analysis software. Also, this tool can be used to perform large scale SIF calculations very easily. Based on these calculation results, the SIF regression equations can be developed, as demonstrated in this paper. In summary, this new tool: *SA-CrackPro* can provide efficient and satisfactory solutions to pavement crack propagation analysis.

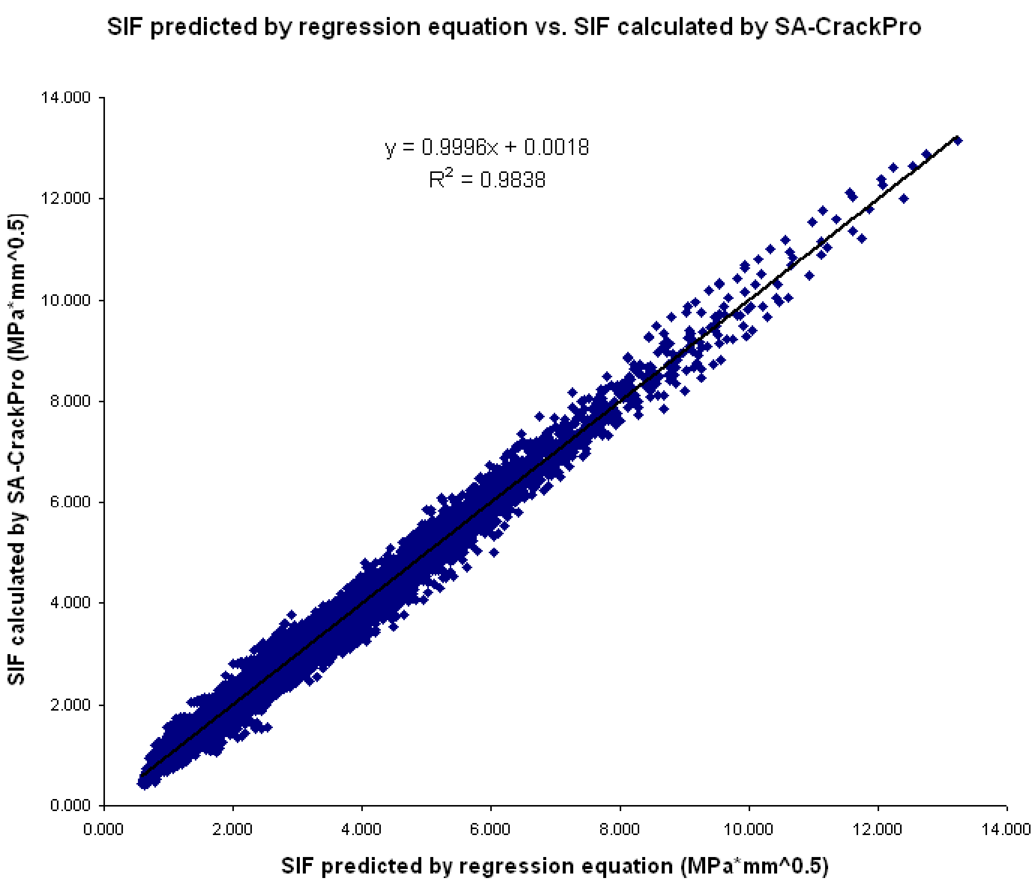


Figure Q-9. SIF predicted by regression equation vs. SIF calculated by SA-CrackPro.